TECHNICAL NOTE 368

A Runoff and Soil-loss Monitoring Technique Using Paired Plots

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USDI Bureau of Land Management
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A Runoff and Soil-Loss Monitoring Technique Using Paired Plots

Abstract

Differences in annual runoff and soil loss caused by livestock grazing on arid rangelands can be measured directly from large plots. A low-cost monitoring technique is described which uses rectangular plots, collection tanks, and cumulative mechanical stage-height counters. Annual runoff and soil loss are measured on paired grazed and ungrazed plots. The plots are replicated and the pairing provides a control. Thus the statistical validity of any differences between grazed and ungrazed plots can be assessed. The plots are easy to construct, and can be maintained with as few as one to two visits per year. The system is presently being tested at four separate locations.

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INTRODUCTION

This technical note describes the construction and instrumentation of runoff plots being tested to measure surface runoff and soil loss. Appropriate sampling designs and data analysis methods are also described. While the plots are designed to measure annual runoff and soil loss differences between grazed and ungrazed plots, they are easily adapted to measuring storm-period runoff and soil loss differences. Both grazed and ungrazed plots are located in close proximity to each other so that they have the same slope, aspect, vegetation cover, soil, and precipitation characteristics. The plots are a low-cost, low-maintenance method of monitoring upland rangeland hydrologic condition. Sampling controls and replication allow differences in runoff and sediment yield between grazed and ungrazed plots to be attributed to livestock grazing and allow a level of statistical significance to be attached to the difference. The plot size and measured variables are suitable for validating common runoff and soil-loss models, and thus provide information which can be extrapolated to other areas with similar hydrologic and range-site characteristics.

BACKGROUND

Instream runoff and sediment transport rates are highly variable and are influenced by many factors in addition to changes in land use and watershed condition. Most arid watersheds--even small ones--are hydrologically complex. This is due to large spatial and temporal variations in watershed conditions. Often ungrazed areas such as bedrock rims, gullies, or channels are important source areas for runoff and sediment. Contributions to streams of runoff and sediment from grazed upland areas may be masked by processes in ungrazed areas or channels. Suspended sediment transport, for example, may vary as much as an order of magnitude at a single stream location for a given runoff rate (Beschta, 1985). Thus, instream sediment transport may not be a sensitive indicator of changes in watershed conditions.

Alternatives to traditional instream sampling for direct rangeland watershed monitoring include retention basin studies (Burkham, 1966; Lusby, 1979), simulated rainfall studies (Lusby and Lichty, 1983), erosion transect studies (Blaney and Warrington, 1983), erosion net studies, and erosion condition assessments (Clark, 1974). Small retention basin studies are similar in concept to the plot technique described here, but are less amenable to the design principles of control and replication. Rainfall simulation studies using plots large enough for soil-loss assessments can be carefully designed and controlled, but are labor-intensive and expensive. Also, data from simulated rainfall studies may not be representative of natural runoff and erosion rates because simulated storms generally have little resemblance to natural storms, and temporal variations in infiltration and soil erodibility are not usually sampled. Erosion transect studies and erosion net studies provide soil-loss data, but not runoff data. However, both of these techniques are amenable to replication and control, and are easy to install and maintain. Erosion condition assessments provide relative ratings (without physical units) and are best suited to inventory-type studies.

CONCEPT

Runoff plots equipped with retention tanks have been successfully used to measure long-term runoff and erosion rates. In fact, a 0.01-ac. plot, 72.2 ft. long was the standard runoff unit used to develop soil-loss parameters for the Universal Soil Loss Equation (Wischmeier and Smith, 1978). The plot-retention tank technique of measuring runoff and erosion volumes is extremely accurate, amenable to replication (e.g., several plots per rangesite) and control (locating plots in exclosures), and inexpensive to install and maintain. In addition, data collected can be compared using standard statistical techniques or analyzed using the Universal Soil Loss Equation (USLE), the SCS Curve Number rainfall-runoff technique, or other common runoff or erosion models.

The main disadvantages to using upland runoff plots for directly monitoring rangeland hydrologic condition are (1) the low number of measurable events, (2) equipment failures, (3) improper site selection or plot installation, and (4) difficulties interpreting upslope processes in terms of off-site effects. The plot technique is most applicable when upland soil loss and surface runoff are the issues being addressed by management. Additional considerations in developing rangeland watershed monitoring programs are discussed in Bureau of Land Management Technical Note 369 (Jackson, et al., 1985).

METHODS

Plot Construction

The plots are constructed of low cost and readily available materials, and are easily installed. Cost of materials per plot is about $125, plus $160 for the recording instrument. A list of materials used in plot installation is shown in Table 1. Time required to install the four plots is approximately 10 person-days.

Each plot is 50 ft. long by 10 ft. wide. Side and upper borders are wood planks set about 3 in. into the soil and supported by wooden surveyor stakes (Figure 1). The lower border is a standard metal rain gutter set in the soil with its upper edge at ground level (Figure 2). The gutter is installed at an angle to the slope and with a slight drop to insure movement of sediments through the gutter. A length of angled roof edging is placed in the soil above the gutter and attached so that it overhangs the gutter edge, providing a stable runoff surface into the gutter. The gutter is covered with hardware cloth to prevent rodent nesting. The disturbed area above the gutter is treated with Celltite, a liquid soil sealer which hardens when sprayed on the soil. Figure 2 shows a finished lower border.

Table 1. Material List for Runoff Plots

44	1 in. x 6 in. x 10 ft. treated boards
2	bundles 18 in. surveyor stakes
3	lbs 8 penny galvanized nails
4	10 ft. metal rain gutters
12	10 ft. metal corrugated downspouts
4	10 ft. type AA angled roof edging
4	gutter end caps
4	gutter connecting sleeves
4	gutter corners
2	tubes latex caulk
	12 ft. x 36 in. wide 1/2 in. mesh hardware cloth
	baling wire
	twine
	fencing materials
	Celltite soil sealer
4	mechanical float counters
4	100-200 gal. stock water tanks

Figure 1. Photograph of plot borders.

Figure 2. Photograph of lower plot border.

All water and sediment collected in the gutter is transported to a collection trough via a downspout. Figure 3 shows a 30-ft. length of downspout ending at a collection trough set in the ground with its upper edge slightly above ground level. Depending on the slope of the terrain, the downspout length can be varied so that the trough rests on the ground surface or slightly below. This makes installation and maintenance easier. In any case, the downspout should be set so that a constant slope is maintained to the trough to prevent sediment deposition.

The collection tank is a 100 or 200 gal. oval stock watering trough. Water level in the tank is recorded by a mechanical float counter, described below, which will cumulatively measure increases in stage. Decreasing water level due to evaporation will not affect the readings. The counter is designed to be read yearly. The readings are converted to a depth, then multiplied by the area of the tank to calculate an annual runoff amount after precipitation has been subtracted. Sediment yield will also be measured at this time.

Instrumentation

There are many ways to measure runoff and sediment delivered to the retention tanks. In fact, for detailed storm period data, traditional methods of stage-height recording and automatic sediment sampling should be employed. However, this system is capable of collecting annual runoff and soil-loss data with as few as 1-2 maintenance visits per year. In arid areas, the retention tank (or basin) concept traps all inflowing waters and sediment. If the water evaporates during dry periods, sediment delivery (or, in this case, soil loss) can be measured directly by collecting and weighing the accumulated sediment. A delivery rate in units of mass over time is determined by dividing by the length of time, in years, since the last cleaning and weighing of sediment in the tank.

Total runoff is more difficult to measure, because of evaporation losses. To solve this problem, a cumulative mechanical water-level recorder that keeps track of the total delivery of runoff to the retention tank was designed for this project. The recorder, designed to be maintenance-free, is being tested on the plots constructed for this project.

The cumulative water-level recorder, available from the Federal Interagency Sediment Project, consists of an open-ended belt with a float attached to one end and a weight to the other end (Figure 4). The belt hangs from a pulley mounted on a horizontal shaft (Figure 5). A mechanical rotary counter is attached to one end of the shaft and a roller clutch is located in a support block at the other end of the shaft. A roller clutch looks like a roller bearing and acts like one for one direction of shaft rotation. When the shaft is rotated in the reverse direction, however, the roller clutch locks onto the shaft, preventing rotation. A second roller clutch is located in the bore of the pulley.

The float and counterweight are enclosed within an open 55-gal. barrel turned upside down. The pulley, shaft, and counter are enclosed in a box mounted on top of the barrel (Figure 5).

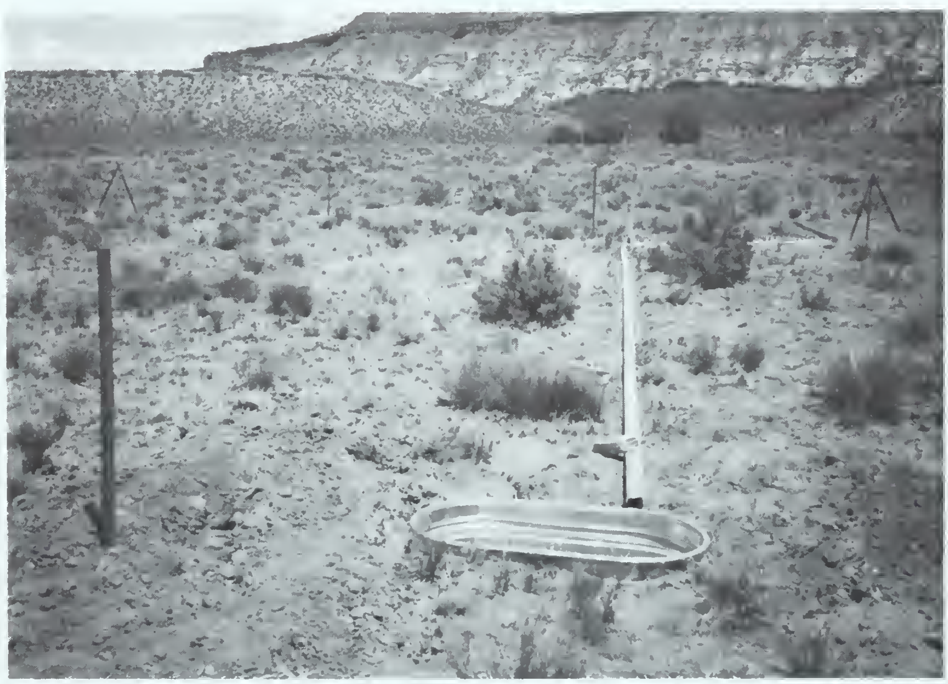


Figure 3. Photograph of Plot Downspout and Collection Tank.

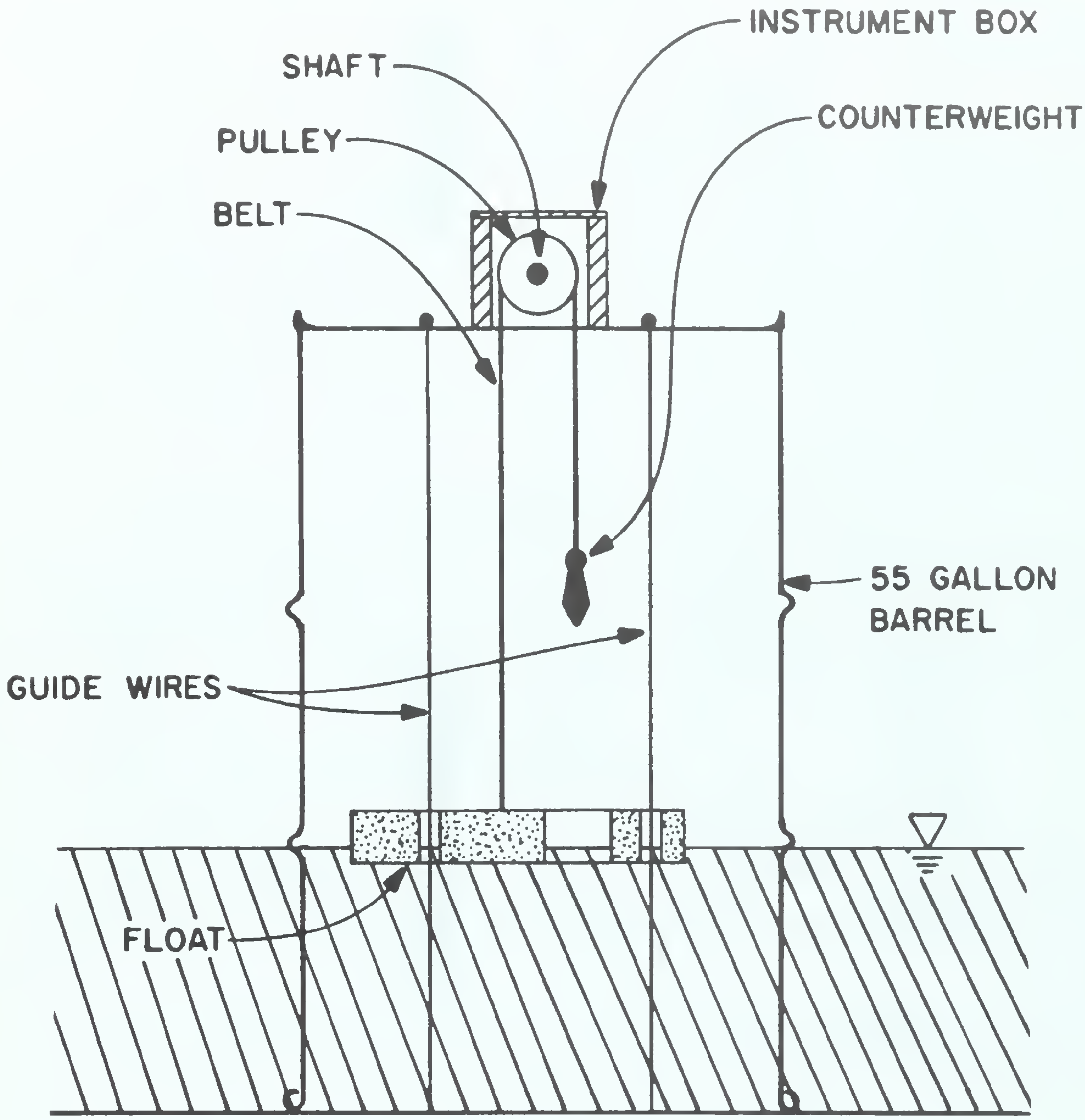
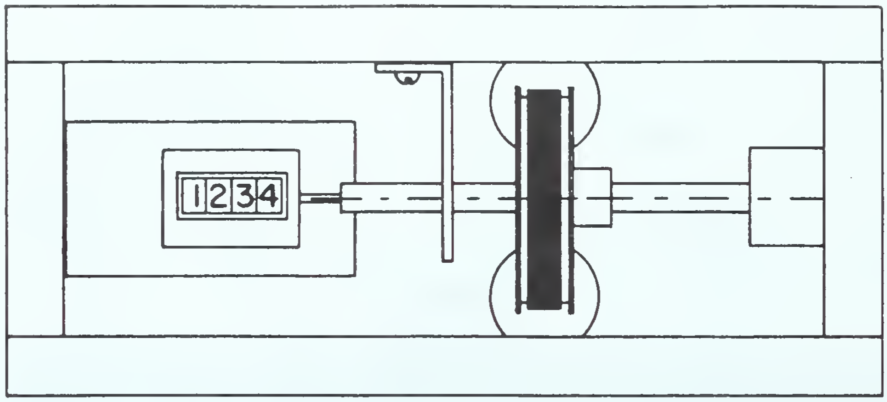


Figure 4. Cross-section View of Cumulative Stage Counter.



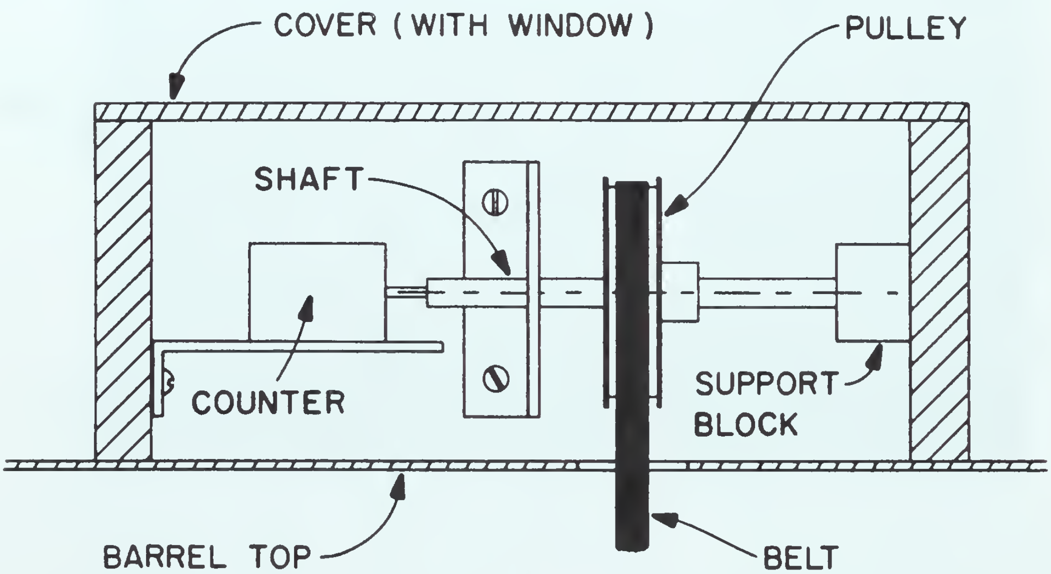


Figure 5. Top View of Cumulative Stage Counter.

As water enters the reservoir, the float is buoyed up off the retention tank floor. The counterweight at the other end of the belt pulls the belt across the pulley causing it to rotate. The pulley's roller clutch locks onto the shaft, turning it and the counter. The counter registers the shaft rotation as long as the float rises. When the water reaches its maximum level, all movement in the recorder ceases.

When water losses occur, the float will fall, causing the pulley to reverse its direction. The pulley's roller clutch now acts as a bearing, and allows the pulley to turn freely on the shaft. The second roller clutch, located at one end of the shaft, locks onto the shaft. Since the shaft does not turn, the counter does not turn backward, but instead remains stationary. The instrument requires about 1/3 in. of water to become buoyant enough to start recording. After that, it records continuously. The rotary counter can be read accurately to about 1/4 in. Installation details for the water level recorder are provided in Appendix I.

STATISTICAL CONSIDERATIONS IN PLOT PLACEMENT

Controls, replication, and randomization are important considerations in plot placement. All three considerations are necessary to evaluate differences in runoff and sediment yield between grazed and ungrazed areas. Though all three considerations are discussed below, a more complete discussion can be found in Bureau of Land Management Technical Note 369 (Jackson, et al., 1985).

Controls

Controls are necessary to attribute any detected change in runoff or sediment yield to grazing, rather than to a climatic change, or some other condition unrelated to grazing.

Replication

The minimum replication is two plots on the fenced exclosure and two plots on the grazed area. Four or five plots in both the exclosure and the grazed area will allow a much smaller difference in runoff or sediment to be detected at a given level of statistical significance than will two plots in each area.

It is not acceptable to establish one plot and measure it year after year. The years are not replications; but are repeated observations on the same plot. Statistics books refer to these as repeated measures (Winer, 1971). If only one plot is established, statistical methods cannot be used in the data analysis.

Randomization

Randomly placed plots will avoid bias. All potential plot locations should have an equal chance of selection. Following is an example which randomly locates three plots on an 8-ac. exclosure.

Randomization process: Example

Only areas at least 50 ft. from the exclosure fence with grasses (no trees or shrubs), slopes of 3-4%, no gullies, and the same soil will be included. The north and south portions of the exclosure have many small gullies which reduces potential plot locations by one-half to one-third.

The 8-ac. exclosure and grid system for this example are shown in Figure 6. The 50-ft. perimeter and the trees in the central portion have been excluded. Cutting the grid density in half for the north and south portions gives those areas less than half the chance of selection of the central areas, which is in proportion to the lower number of suitable plot locations in the north and south areas.

Final plot locations are selected by numbering all the intersections within the boundaries and randomly selecting a number between 1 and 43 (the number of plot locations) for each of the three desired plots. Find the selected grid locations in the field, then walk north and locate the plot in the first suitable location within 10 ft. to either the right or left. The map doesn't have to be perfect. The object is to try to give all suitable plot locations an equal chance of selection.

ANALYSIS OF COMMON SAMPLING DESIGNS FOR RUNOFF PLOTS

Design A. This design has only one plot and thus no control or replication, and should not be used. Let's assume you are not responsible for the design, but are responsible for evaluating 20 consecutive years of data collected from one plot.

Possible analyses: Regression can be used to quantify a change over time, but the significance levels of the slope (B) and the r^2 values are overestimated. However, the computed slope, B, is a valid estimate of the yearly change over time. This overestimate of r^2 and the significance level of B is caused by lack of independence between the yearly values, which violates the assumptions of the regression, and thus invalidates the significance levels of the results. Thus, if the slope is non significant, there is definitely no significant linear trend over time.

In a report, simply make a statement of the facts, such as "over the 20 years, runoff on the plot decreased from 8.6 ft^3 to 4.3 ft^3, averaging .2 ft^3 per year." Don't, however, quote significance levels or r^2 values, since they are incorrect.

Design B. This design has two or more plots on an area of interest, but has no corresponding control. The design will allow probability statements to be attached to a change over time, or confidence limits to be placed on sediment yield or runoff for any given year or group of years. However, because a control area was not measured, it may be impossible to sell the idea that a management action caused a change over time.

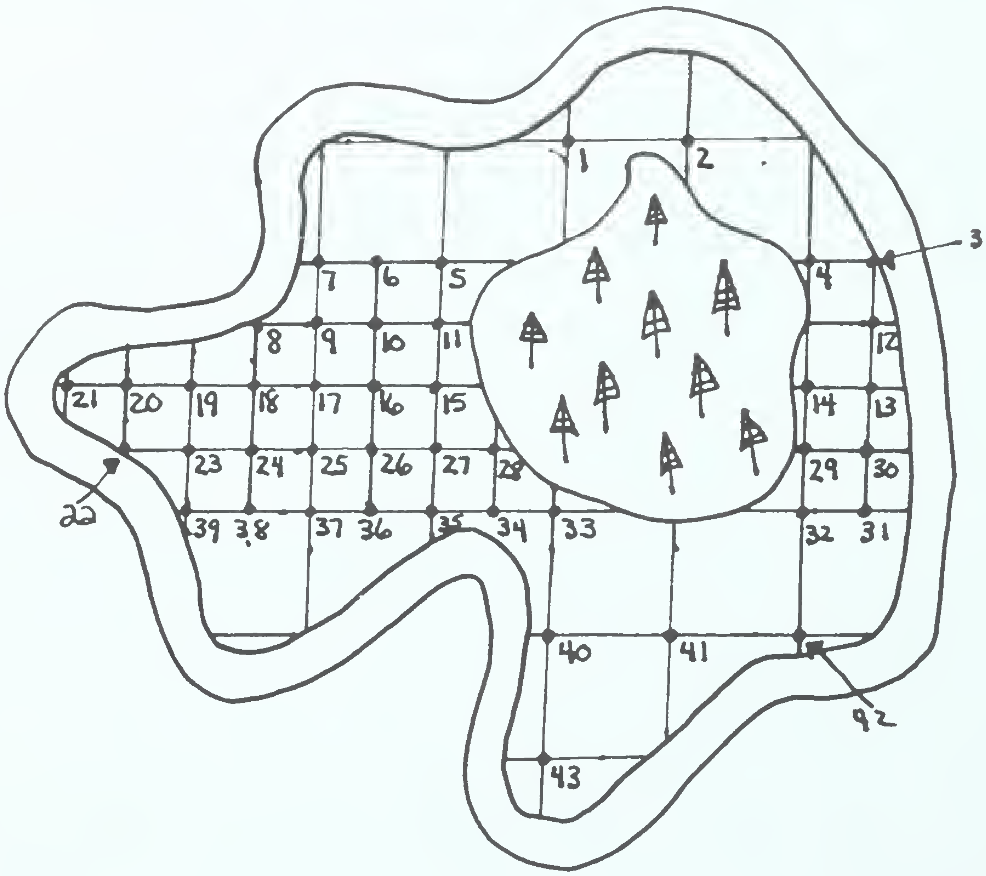


Figure 6. Eight-acre Exclosure and Grid System for Randomization Example.

Analyses: A change over time can be tested using a t-test or ANOVA. The t-test is simple, but not very powerful since the test will have only p-1 degrees of freedom, where p is the number of plots. For each plot, it is possible to quantify differences in annual soil loss or runoff between, say, the first year and the last year, or perhaps the sum of the first three years and the sum of the last three years. The t-test can be used to see if the differences are significantly different from zero. A repeat measure ANOVA, with an orthogonal decomposition of the year sum of squares into linear, quadratic, etc. components, is slightly more powerful (Table 2). The orthogonal decomposition is merely an algebraic method of breaking down an equation (sum of squares in this case) in such a manner that none of the pieces overlap.

Table 2. Example ANOVA Table

line number	source of variation	degree of freedom	significance test
1	year	y-1	MS(1)/MS(2)
	linear	1	MS(lin)/MS(2)
	quadratic	1	
	.	.	
	.	.	
	.	.	
	degree y-1	1	
2	error	y(p-1)	----

where p = number of plots in exclosure
y = number of years
MS(i) = the mean square error for line i

If year (line 1) is significant, check further to see if the linear component is also significant. If the linear component is significant, do a regression to quantitate the change per year, but use the significance level from the ANOVA rather than the regression as explained under "Possible Analyses." In the regression, years will be the independent variable, and runoff or sediment the dependent variable.

Design C. This is the recommended design. It has one exclosure with two or more plots within the exclosure and two or more plots outside the exclosure. Statistical methods can assess differences between the grazed and exclosure areas, as well as any changes over time. The control area allows management to take credit for any detected changes or differences.

Analyses: Two or more plots are nested within the exclosure and two or more plots are nested "outside the exclosure." See Sokal and Rohlf (1969) for more information on nested ANOVA design (Table 3).

Table 3. Nested ANOVA Table

line number	source of variation	degree of freedom	significance test
1	fence	1	MS(1)/MS(2)
2	plots within fence	2(p-1)	---
3	years	y-1	MS(3)/MS(5)
4	(fence) x (years)	y-1	MS(4)/MS(5)
5	(plots within fence) x (years)	2(p-1)(y-1)	---

Where p = number of plots in exclosure
y = number of years
MS(i)= the mean square error for line i

1. If the plots are on an existing exclosure and the change to be detected has already occurred, then look for a significant F value on line 1. This would indicate a significant difference between the fenced and unfenced plots. For only 1 year, lines 3-5 are not present and the test becomes a two sample t-test with degrees of freedom = 2(p-1).

2. Plots on a newly created exclosure and plots on the grazed area should have the same runoff and sediment yield at year one, the time at which the exclosure was created. Over the years, improvement might be expected on the exclosure but not on the grazed area. If this is true, line 4, the interaction between fence and year, will be significant. If the interaction is significant, the difference in runoff and sediment yield between the fenced and unfenced plots over time should be further investigated by analyzing the fenced and unfenced plots separately.

   These separate analyses are done via one-way repeated measure ANOVAs (Table 4) (Winer, 1971).

Table 4. One-way Repeated Measure ANOVA Table

line number	source of variation	degree of freedom	significance test
1	years	y-1	MS(1)/MS(2)
	linear	1	MS(lin)/MS(2)
2	plots within years	(y-1)(p-1)	- - -
3	between plots	p-1	- - -

Where y = number of years
p = number of plots
MS(i)= mean square error for line i

The mean square for years can be broken down into linear, quadratic, etc. terms up to degree y-1. See page 12 "Analyses," for an explanation. If there is a constant change over time, the linear component will be significant and a regression can be done to compute the slope of the line. The slope of the line is the increase or decrease in sediment or runoff per year. However, the regression overestimates the significance of the slope and the r^2 values, so don't make decisions which rely on them.

Design D. This design has two or more exclosures with one plot per exclosure, plus two or more grazed plots. It answers the same questions as Design C and has the same precision. Design D is more expensive than Design C to install since separate exclosures must be built for half the plots.

Analysis: Same as Design C.

IMPLEMENTATION

Plots should be located in the range site of interest to management. Unless an existing exclosure can be utilized for the control plots, a new exclosure will be required. Also, information on runoff and soil loss will be most useful in conjunction with corresponding monitoring information on rangeland vegetation. Thus it may be desirable to coordinate runoff plot locations with vegetation monitoring sites. Once the homogeneous site of interest is selected, individual plots should be sited randomly as described previously.

Of the plots constructed for this project, four each are located on:

1) Glaciated plains east of Havre, Montana,
2) Big sagebrush rangeland northwest of Elko, Nevada,
3) Fine, alluvial rangeland south of Hurricane, Utah, and
4) Silty salt-desert rangeland south of Naturita, Colorado.

All plots were constructed in the summer of 1984. The exclosure for the Hurricane plots had been in place for 3 yrs. at the time the plots were constructed. All other control plots were fenced at the time of construction. Detailed descriptions of each plot-monitoring site were prepared at the time of construction and are available from the local Bureau of Land Management Office. Data will be analyzed as described for sampling Design C above.

To date, runoff events have occurred on all 16 plots. While the plots and instruments have, in general, performed as planned, problems have been identified and some minor modifications in construction may be required. Possible improvements to be considered include a solid PVC-type drain spout, use of fabric in combination with soil sealant at the lower plot border, frequent (e.g., annual) applications of soil sealant, larger (e.g., 200 gal.) retention tanks in higher rainfall areas, better screening of tanks to keep out small animals, improved leveling of the float-counter, and improved sealing of plot borders in active (shrink/swell; freeze/thaw) soils. In addition, a lid will be required on retention tanks located in areas of blowing snow. When it is necessary to set tanks deep in the ground, additional screening from blowing soil is required, and cleaning sediment from the tanks is more difficult. Recommendations for modifications or improvements will be made after additional analysis of field performance.

CONCLUSIONS

Replicated pairs of runoff plots can be used to monitor directly changes in upland runoff and soil loss caused by livestock grazing. The plots allow a statistical significance to be placed on annual difference in runoff and soil loss between grazed and ungrazed plots. The plots are easy and inexpensive to construct, and, when instrumented with a cumulative stage counter, may be maintained with as few as one to two visits per year. Optional instrumentation would permit storm-period data to be collected. The plot design and cumulative stage counters developed for this project are currently being tested at four separate field locations.

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Appendix I

Instructions For Assembly of the Cumulative
Water-Level Recorder

Appendix I

INSTRUCTIONS FOR ASSEMBLY OF THE CUMULATIVE WATER-LEVEL RECORDER

The cumulative water-level recorder is shipped in the following parts and subassemblies:

1) 55-gal. barrel
2) recording instrument
3) float, belt, and counterweight
4) anchor rod
5) stainless steel wire
6) Fiberglas filter material
7) bag of fasteners

Much of the assembly can be done in the shop prior to field installation. The recorder must, however, be protected while transporting it to the field when pre-assembled.

Assemble the recorder as follows:

1) Connect the instrument to the 55-gal. barrel. First be sure that the instrument sits reasonably flat on top of the barrel. Align the instrument so that the ends of the pulley are directly above the two large holes and that the two mounting brackets are aligned with the matching holes in the barrel./1 Apply caulk or silicone sealant to the bottom of the instrument box, reposition it on the barrel, and secure it with the #8-32 x 1/2 machine screws, lock washers, and nuts. Holes in the barrel may have burrs and sharp edges; appropriate caution should be used.

2) From outside of the barrel, pass two lengths of straightened stainless steel wire into the two inner holes on the barrel head. These holes (14 in. apart) are located on opposite sides of the instrument. Pass the wire through the barrel until it emerges from the open end of the barrel.

3) In a similar manner, pass a length of string or cord through the large hole at the take-up end of the pulley. This is the upper of the two large holes when viewed as if reading the counter.

4) Tie the string to the counterweight and orient the float so that the belt is aligned with the hole that the string passes through and that the two 1/2 in. holes in the float are aligned with the holes the wires pass through./2 Feed the wires through the matching holes in the float. Push the float into the barrel while holding onto the wires. Pull the counterweight and belt through the hole under the pulley.

5) Push one cotter pin into the hole at one end of the anchor rod. Push the rod through the matching holes at the open end of the barrel. Secure the rod in place by installing the second cotter pin in the rod end protruding from the barrel.

6) Insert the wires in the matching holes in the anchor rod. Wrap each wire around the rod and twist the free ends to the straight portion of wire that emerges from the rod. Make this tie as small and tight as possible. Nip-off the wire ends.

7) On the barrel head, locate the outer holes adjacent to the holes from which the wires emerge. Slip a washer onto each self-tapping screw and screw halfway into the outer holes. Pull each wire, one at a time, so that it is taut. Do not pull hard enough to bend the anchor rod. Wrap each wire around the shank of the adjacent screw and secure by tightening the screw to the barrel head. Do not strip the self-tapped thread. /3

8) Apply caulk or sealant over all holes and screw heads outside of the instrument box. This includes the inside diameter of the anchor rod. Caulk the outer edge of the instrument box, if desired. The barrel should be watertight except for the open end and the inside of the instrument box.

This completes the shop assembly.

FIELD INSTALLATION

The barrel should be located where it will be level and where the water surface will be the least disturbed. Cut 70 in. of fiberglass insulation. Fold the insulation in half along its length. Disposable gloves may be advisable when handling fiberglass. Keep fiber particles away from eyes and skin. Place the barrel in mounted position. Tuck the insulation under the lip of the barrel for the entire circumference. Be sure that no insulation interferes with the float. There should be no gaps in the insulation or areas where insulation is not fully compressed. Also, the barrel must be level. Make any needed adjustments to the fiberglass. The barrel can be secured in place by cross supports across the top of the retention tank, or by bolting to the bottom of the tank.

The insulation acts as a filter, keeping sediment and debris outside of the barrel. The tightly compressed insulation also is necessary to dampen fluctuations in water level. Without this dampening, slosh and wave motion will be recorded. A delay in the recording of a rising water level is not detrimental.

CALIBRATION

The recorder may be calibrated in the shop or in the field. A field check is more desirable, but may not be practical where water isn't readily available.

One revolution of the pulley is equal to about 7 in. of rise in water level. One revolution also registers as 10 counts on the counter. The counter, therefore, records about 3/4 in. increase in stage per count. Interpolating between counts should give results to the closest quarter in. Further precision in readout is unnecessary due to the magnitude of inherent errors in the recorder.

The vinyl covered fiber belt may become more supple over time. This would primarily be due to exposure to elevated temperatures. It may be advisable to recalibrate the recorder after this occurs.

For additional information, contact the Federal Interagency Sedimentation Project at FTS 787-3352 or (612) 349-3352.

/1 Stack flat washers under one bracket to level the instrument (if necessary).

/2 The bottom side of the float has a 1-in. wide channel, the top does not. The arrow on the bottom side of the float should point toward the "X" marked on the inside of the barrel. This will position the belt below the proper hole in the barrel head.

/3 Remove the string from the sinker. Gently pull the float toward the instrument. If necessary, twist the belt so that the length between the float and your hand is flat (untwisted). Feed the sinker through the second large hole beneath the pulley. The belt should be lowered onto the pulley so that the belt remains untwisted.

/4 The bolt should pass through a flat washer, the reservoir, and a second flat washer. Tighten down a nut onto the bolt. Hold this bolt in position with a wrench; then tighten a second nut onto the bolt using a second wrench. This will lock the two nuts together.

/5 Use two wrenches. One wrench must be used to hold the lowermost nut in place.

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